On Criterions of Stability of Fans Operating in Parallel

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ABSTRACT

Ventilation systems with fans operating in parallel may have multiple operating points. The submitted paper presents a method which enables to reduce the number of points which should be taken into consideration. The concepts of a fan system containing: the fan, inlet duct, regulation door subsystem and its total characteristics were introduced. The analysis of local stability of equilibrium points of the system of ordinary differential equations describing unsteady incompressible flow in a simplified network ventilated by 2 fans in parallel leads to formulation of a simple condition of stability. For fans operating in parallel this condition refers to the slopes of fan systems characteristics, excluding the possibility of stable parallel operation when all fan subsystems operate such that their operating points are on the rising parts of characteristics. To satisfy this requirement at least one fan system must operate on a sufficiently falling part of its characteristics when the remaining ones have their operating points on the rising part. Some graphic examples of construction of ventilation systems characteristics are presented. Results of calculations were graphed to show time variations of flow quantities and pressure during transients caused by the loss of stability.

KEYWORDS

Ventilation, fan stations, stability, fans, ventilation networks, unsteady states, computer simulation.

INTRODUCTION

In main fan stations fans are often combined in parallel. An example of such solution is the three –fan station wherein two fans installed in parallel provide the ventilation and the third one is kept in reserve. Owing to the presence of the third fan, the maintenance and repairs can be done without shut-downs. When the third fan is standing by with its regulator being tightly closed, it can be excluded from the network analyses.

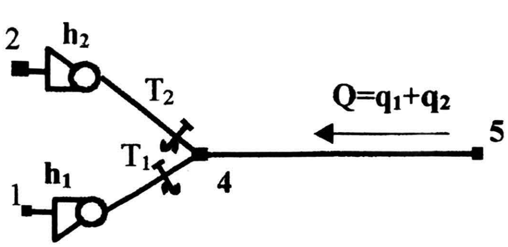

Figure 1. Simplified scheme of a network of two fans operating in parallel.

Accordingly, Figure 1 will represent the schematic of a simplified network ventilated by two fans connected in parallel. The branches 4-1 and 4-2 are inlet ducts; while the remaining part of the network is represented by the simple branch 5-4 whose resistance equals that of the combined network. The by-pass and regulators systems used for fan reversal are not included in the scheme. The nodes 1,2,5 are duct inlets and outlets. It is assumed that the static pressure p_{ATM} in their direct neighborhood remains the same. To determine the ventilation conditions we have to first obtain the pressure – mass (or volume) curves. They will be called the characteristic curves for the network and the fan station, respectively. Let us first consider the fan – network system (the regulator T_2 being closed and the fan 2 – switched off). If we neglect leakage across T_2, the mass flow q_1 entering the channel 4-1 can be considered as equal to the mass flow Q supplied from the network to the node 4. Accordingly, the operating point of the fan will be determined from the condition:

$$h_1 = W_t \tag{1}$$

where h_l is the static pressure developed by fan 1 and W_t are total pressure loses in the network.

The term W_t can be partitioned into the losses w_l in the fan inlet duct 4-1, including the losses caused by the regulator T_1 and the remaining part named W. Adding w_l and W we obtain W_t. Then the equilibrium condition can be expressed in terms of the static pressure difference for the fan- inlet duct system Δp_1 and pressure loses W in the remaining part of the network:

$$\Delta p_1 = W \tag{1a}$$

where $\Delta p_1 = \Delta p_1[q] := p_{ATM} - p_4 = h_1 - w_1$ includes the effects of the diffuser (in term h_l) and the pressure losses w_l. Total loss of pressure across remaining part of the network can be expressed as $W = W[Q] := p_{ATM} - p_4$. When the pressure – mass flow curves are graphed, the condition (1a) will be then satisfied at the intersections of the characteristic curves of the network and the fan station. Figure 2 presents some characteristic curves for the network and the station. It is assumed that the losses at the network inlet (node 5) and the fan outlet (node 1) are taken into account and so are the effects of the diffuser and the losses along the duct.

While designing a ventilation system we try to select the characteristic curves such that it should operate at the point D. For axial fans the characteristic curves for the station may have its local peaks and minimum points. Thus for certain values of the resistance (curve II on Figure 2) we get three operating points for the station. Considerations presented by W. Trutwin in [Kruszyński & Trutwin, 1972] lead to well known conclusion that at the operating point B, where the characteristic curve of the fan is steeper than that of the network, fan operations will not be stable. This condition can be thus written as:

$$h' := \frac{d(h[Q])}{dQ} < \frac{d(W_t[Q])}{dQ} =: W_t' \tag{2}$$

Which can be expressed in terms of Δp and W as:

$$\Delta p' := \frac{d(\Delta p[Q])}{dQ} < \frac{d(W[Q])}{dQ} =: W' \tag{2a}$$

The derivatives $\Delta p'$ and W' denote the slopes of the system characteristics. Condition (2) is often called the static criterion of equilibrium [Bystroń, 1973].

When axial fans are connected in parallel, the combined characteristic curve of the station may become very complex [Figure 6]. In the case of most complicated ventilation systems it is necessary to solve the systems of non-linear equations [Lin & Wang, 1993].

For serial or parallel combinations, the graphic construction can be applied [Budryk, 1935]. Let us concentrate on a subsystem of the ventilation network presented in Figure 1, this subsystem consisting of a fan with a diffuser, an inlet duct and the regulator. It will be then called the fan system, as delineated with a broken line in Figure 3.

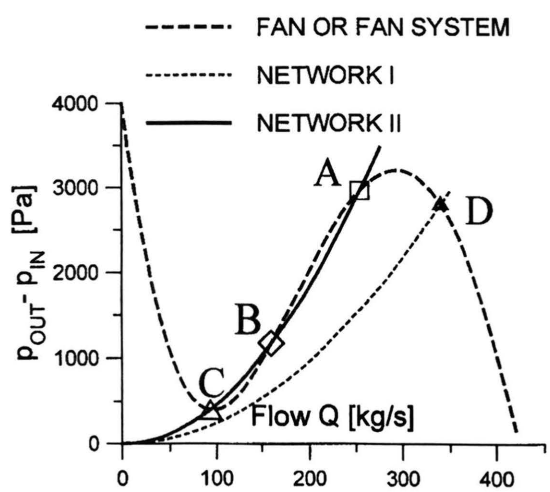

Figure 2. Characteristic curves of the network and the single-fan station.

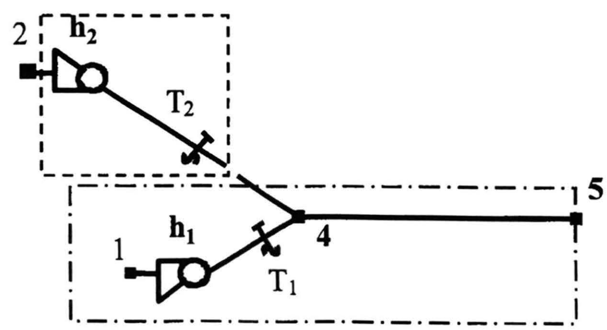

Figure 3. The network and the fan system.

The characteristic curve of the fan system will be that defining the relation between the mass flow rate q_i at the i-th duct inlet cross-section and Δp_i.

When the regulator is closed, the pressure loss w across this component will increase and the characteristic curve of the whole fan system will move down. The influence of pressure loses w on the total fan system characteristic curve $\Delta p(q) := h(q) - w(q)$ is shown in Figure 4.

When defined above (see Figure 3) fan system (fan 2 and branch 4-2) is conceptually excluded from the network, the remaining part of the system will be the parallel combination of the fan system 4-1 and the branch 5-4.

Applying the method presented in [Budryk, 1935], we can construct the characteristic of such a system. It considers the effects of any value of pressure head $p_{ATM} - p_4$ on the total flow quantity flowing from node 4 into the excluded fan system 4-2.

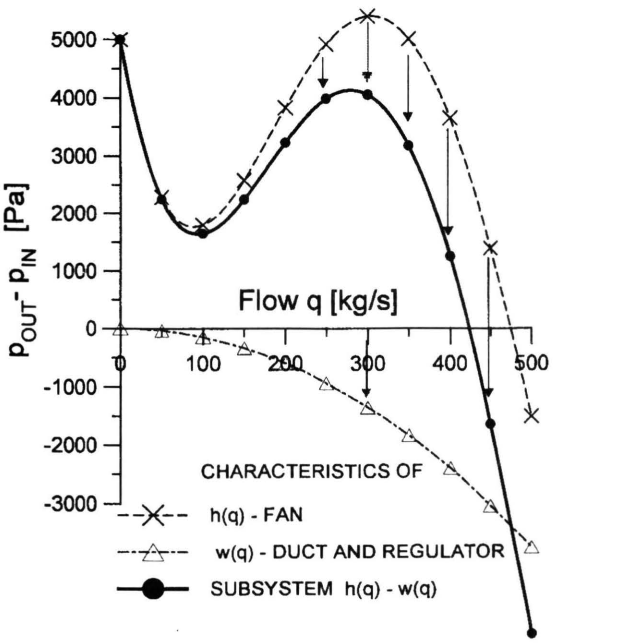

Figure 4. The characteristic curves of the fan, the inlet duct and the regulator operating in series.

Figure 5 presents the characteristic curve of the first fan and that of the branch 5-1 *W[Q]*. The total flow quantity leaving the parallel combination can be found from the flow balance at the node 4.

$$q_2 = Q - q_1 \tag{3}$$

For the given value of p_{ATM} - p_4 found on the characteristics of the branch 5-4 we find the point $X(Q, W[Q])$ and the point $Y(q_1, \Delta p_1[q_1])$ of the characteristic curve of the first fan. For parallel combination we can find the corresponding point $Z(Q - q_1, p_{ATM} - p_4)$ on the combined characteristic of the system. Figure 5 considers the case when three points Y can be found for particular value of pressure difference and in consequence three Z points should be drawn (the square and triangle symbols refer to remaining two pairs of Y and Z points).

In Figure 6 fan and branch system characteristics $\Delta p_i(q_i)$ are drawn for both systems (solid lines). Although fans itself and their characteristics $h_i(q_i)$ were identical, the system characteristics are different due to larger pressure loses w_2 in the branch 4-2. Curves to the right refer to conceptual division presented in Figure 3. Dash-dotted line is the characteristic of the subsystem 4-1 and 5-4 in parallel (see Figure 5). It is compared with $\Delta p_2(q_2)$ - the second fan-branch 4-2 subsystem characteristic. Analogous curves to the left refer to the case when the first fan system is excluded.

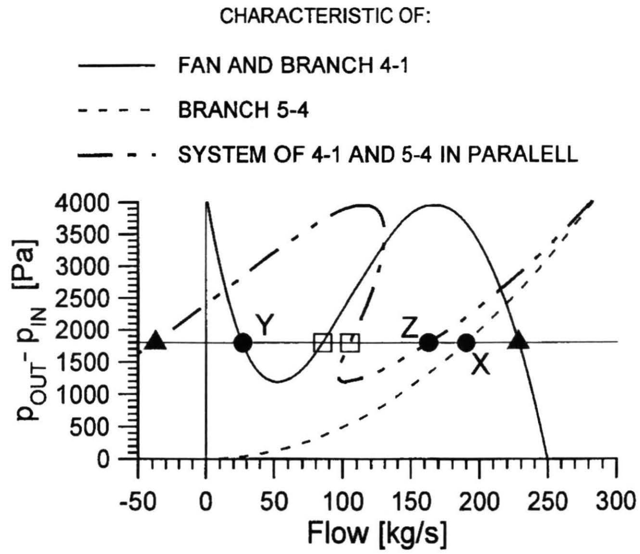

Figure 5. Combined characteristic of the branch 5-4 and the first fan system $\Delta p_1(q_1)$ operating in parallel.

The condition relating to accordance of pressures at the node 4 and mass conservation (3) are satisfied at the intersections of these characteristic curves. For the characteristic curves presented in Figure 6 we get 3 possible operating points of the network. These are designated with "A", "B", "C".

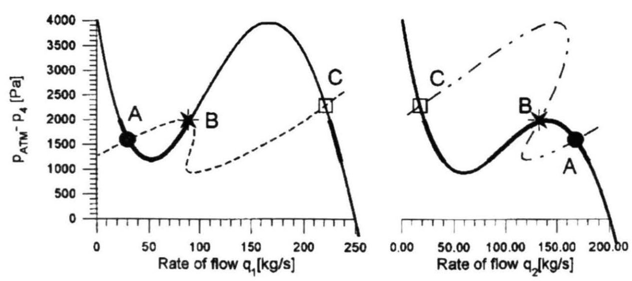

Figure 6. The characteristic curves of the excluded fan systems and the remaining portion of the network for both fans.

We can conceptually divide the network into subsystem in a different way, too: the branch 5-4 may be excluded while the fans in 4-1 and 4-2 will make up the fan station. The combined characteristic of the units 4-1 and 4-2 is presented in Figure 7 (solid lines). They operate in parallel, the flow rate $Q = q_1 + q_2$ is supplied from the branch 5-4 to the station. The steady flow through the network is possible only in those states that correspond to the intersections of those curves with the characteristic of branch 5-4 (dashed line). They are designated as "A", "B", "C", as in Figure 6. Thicker lines in the Fig 6 refer to those sections of the fan systems characteristics which in parallel combination form this portion of the station characteristic which resembles the symbol " ∞ " (see Figure 7).

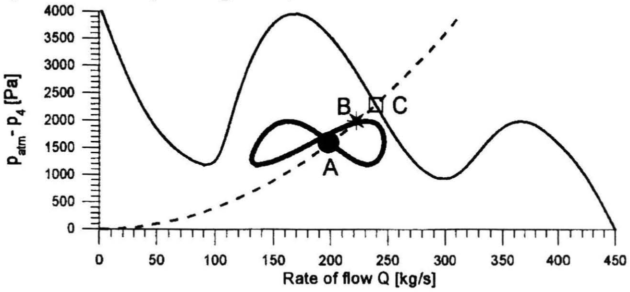

Figure 7. Characteristic curve of the station and the remaining portion of the network.

It can be demonstrated that when the characteristic curves of the fans are such that the characteristic curve of the network should intersect them at three points (as in Figure 2), then for parallel fan combinations the resultant characteristic curve of the station may intersect that of the network at $3^2 = 9$ points. That would mean that such fan station might have up to nine operating points. In normal working conditions the fan parameters are chosen such that they operate throughout the range recommended by the manufacturers, that is have their operating points on the falling part of the pressure – flow rate curve, to the right of the peak. However, one can image some specific conditions when the ventilation system should have several equilibrium points, as shown in Figure 6 and 7. Accordingly, the question arises whether the stability condition can be formulated analogous to (2).

When we assumed that it suffices when the characteristic curve of the station is less steep that that of the network, then all points "A", "C" and "B" would correspond to stable operation. However, the calculations for simple models of unsteady flows lead us to the conclusion that minimal divergences from the equilibrium point "B" cause the flow to change and finally reach the state "A" or "C", which indicates that the point "B" is not stable.

Therefore, local stability of the simplest system of differential equations describing unsteady flows through the network was investigated.

STABILITY CRITERION

Assuming air incompressibility, the simplified model of a one-dimensional flow in a single ventilation conduit [Litwiniszyn 1951, Trutwin 1972] can be written in the form of the equation:

$$p_{OUT} = p_{IN} + h[q] - W_t[q] - \beta \frac{dq}{dt} \tag{4}$$

where: p_{IN} – static pressure at the inlet, p_{OUT} – static pressure at the outlet,

$$\beta := l / A \tag{5}$$

denotes the acoustic mass, l- branch length [m]; A- its cross section area [m^2] q- mass flow rate [kg/s]. The static pressure difference developed by the fan and the diffuser is denoted as h; while W_t stands for: the total frictional pressure loss in the conduits, that due to regulating dampers, inlet and outlet loses. Let us formulate analogous equations for the flow route 5-4-1 and 5-4-2 (Figure 1) using (3) and assuming that the pressures at the boundary nodes 1,2,4 are equal p_{ATM}:

$$\begin{cases} h_1[q_1] - w_1[q_1] - \beta_1 \dfrac{dq_1}{dt} - W[Q] - \beta \dfrac{dQ}{dt} = 0 \\ h_2[q_2] - w_2[q_2] - \beta_2 \dfrac{dq_2}{dt} - W[Q] - \beta \dfrac{dQ}{dt} = 0 \end{cases} \tag{6}$$

where β, β_1, β_2 denote the acoustic masses (5) for the branches 5-4, 4-1, 4-2.

The flow rate Q can be expressed as function of q_1 and q_2 (from (3) $Q = q_1 + q_2$), so (6) becomes a system of equations linear with respect to the derivatives dq_1/dt and dq_2/dt as the functions of q_1 and q_2, so those derivatives can be obtained from this system of equations. Accordingly, (6) will be equivalent to the following system of equations:

$$\begin{Bmatrix} \dfrac{dq_1}{dt} \\ \\ \dfrac{dq_2}{dt} \end{Bmatrix} = \begin{Bmatrix} f_1(q_1, q_2) \\ \\ f_2(q_1, q_2) \end{Bmatrix} \tag{7}$$

In the state of equilibrium of the system, designated with E the values of q_1 and q_2 are such that the time derivatives of flow rates in (7) equal zero:

$$f_1(q_1, q_2) = f_2(q_1, q_2) = 0 \tag{8}$$

Therefore they will be denoted as q_{1E}, q_{2E}. Lack of stability of such an equilibrium point may be predicted while studying the linear approximations of the equation (7) in the neighborhood of E:

$$\begin{Bmatrix} \dfrac{d\hat{q}_1}{dt} \\ \\ \dfrac{d\hat{q}_2}{dt} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial f_1(q_1,q_2)}{\partial q_1} & \dfrac{\partial f_1(q_1,q_2)}{\partial q_2} \\ \\ \dfrac{\partial f_2(q_1,q_2)}{\partial q_1} & \dfrac{\partial f_2(q_1,q_2)}{\partial q_2} \end{Bmatrix}_E \begin{Bmatrix} \hat{q}_1 \\ \\ \hat{q}_2 \end{Bmatrix} \qquad (9)$$

where $\hat{q}_i := q_i - q_{iE}$, $i = 1,2$ denote the flow rate deviations from the value at the point E while $\{\partial f_i / \partial q_j,\ i,j = 1,2\}$ is the Jacobean matrix of the system of equation (7), computed for the point *E*. This matrix will have the form:

$$\begin{Bmatrix} (\beta_2 + \beta)\Delta p_1' - \beta_2 W' & \beta \Delta p_2' - \beta_2 W' \\ \\ \beta \Delta p_1' - \beta_1 W' & (\beta_1 + \beta)\Delta p_2' - \beta_1 W' \end{Bmatrix} invB \qquad (10)$$

where $invB = \dfrac{1}{\beta_1 \beta_2 + \beta(\beta_1 + \beta_2)}$ is a constant, depending on the acoustic masses of the branches, $\Delta p' := \dfrac{d}{dq_i}(h_i - w_i)_E$ $i = 1,2$ - the tangent of the angle of fan system characteristic slope less the tangent of the slope duct resistance characteristic (including the regulator resistance). Similarly, *W'* stands for the slope of the characteristic curve of the remaining portion of the network, that is the branch 5-4. Let us introduce dimensionless slopes for both equivalent characteristics of considered fan, inlet duct and regulator systems:

$$n_i := \Delta p_i' / W' \qquad (11)$$

When the combined characteristic of the fan system $\Delta p_i[q_i]$ is steeper than $W[Q]$, then $n_i > 1$.

The stability of the system (8), according to the Hurwitz criterion, will have the form of two conditions:

$$(\beta + \beta_2)n_1 + (\beta + \beta_1)n_2 - (\beta_1 + \beta_2) < 0 \qquad (12)$$

and

$$n_1 n_2 - (n_1 + n_2) > 0 \qquad (13)$$

The first of these conditions is satisfied when (n_1, n_2) are located to the left and below the straight line (see Figure 8) which intersects the axis n_1 for $\hat{n}_1 = (\beta_1 + \beta_2)/(\beta + \beta_2)$ and the axis n_2 for $\hat{n}_2 = (\beta_1 + \beta_2)/(\beta + \beta_1)$. The other condition is satisfied upwards right and downwards left from the hyperbola defined in (13). Acoustic masses (5) are positive therefore line (12) cannot be located beyond point (1,1) in

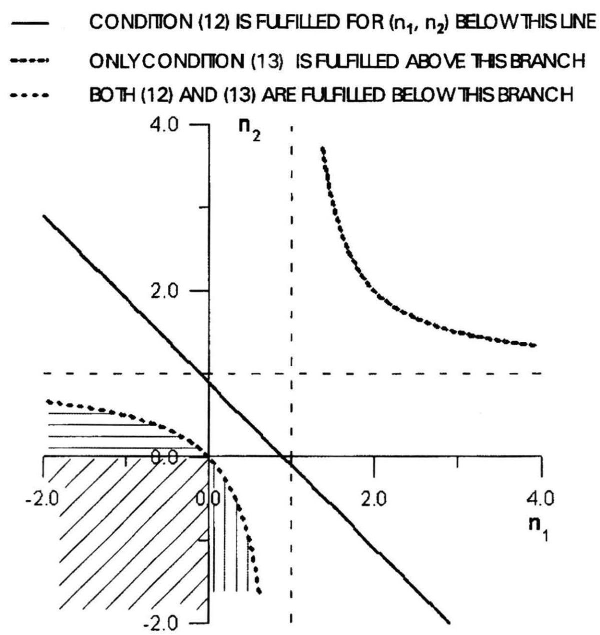

Figure 8. An illustration of the stability criterion (12) and (13).

the (n_1, n_2) plane and will not intersect the upper right branch of the hyperbola (13).That is why both conditions will be met by (n_1, n_2) located in the region below the lower branch of the hyperbola (striped area in Figure 8).

In this region there are no points from the first quarter of the co-ordinate system. That means that parallel operation of two systems of a fan, a regulator and an inlet duct is impossible when both combined characteristics $\Delta p_i(q_i)$ are rising– the stability will be lost. It does not necessarily mean that the fan itself cannot have its operating points on the rising part of the characteristic – for the system the resultant inclination equals that of the fan characteristics diminished by the slope of the regulator and duct characteristic (see Figure 4). Should the resistance of regulator *T* be large enough, the combined characteristic of the whole fan system will be falling.

The static stability criterion allows:

1. stable co-operation when both fan systems operate on the falling slopes of their characteristics. On the (n_1, n_2) plane it refers to the third quarter of the co-ordinate system $(n_1<0,\ n_2<0)$ – in that case the combined characteristic curve will be falling
2. operation on the rising part of the station characteristics when (n_1, n_2) are located below the left branch of the hyperbola in the second or the fourth quarter of the co-ordinate system (horizontally or vertically stripped area on Figure 8). In this case one slope is positive and the other must be falling enough to satisfy (13).

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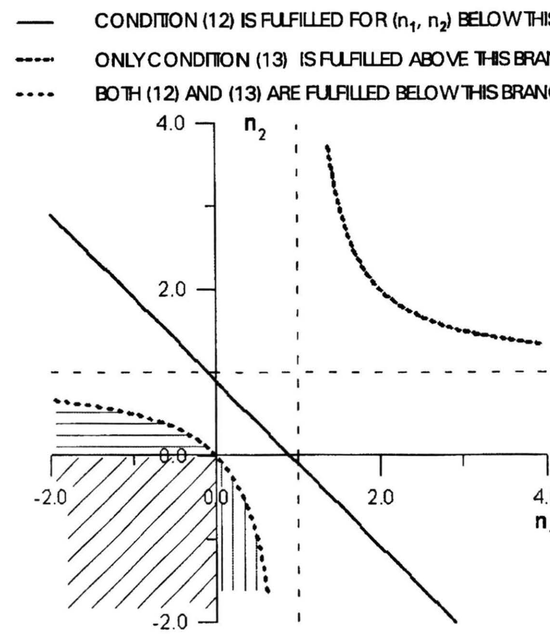

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In this region there are no points from the first quarter of the co-ordinate system. That means that parallel operation of two systems of a fan, a regulator and an inlet duct is impossible when both combined characteristics $\Delta p_i(q_i)$ are rising– the stability will be lost. It does not necessarily mean that the fan itself cannot have its operating points on the rising part of the characteristic – for the system the resultant inclination equals that of the fan characteristics diminished by the slope of the regulator and duct characteristic (see Figure 4). Should the resistance of regulator *T* be large enough, the combined characteristic of the whole fan system will be falling.

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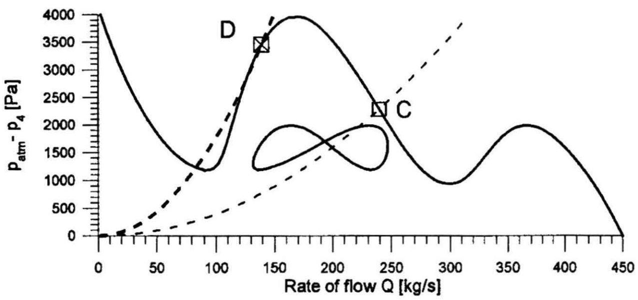

Figure 13. Location of the operating points 'C" and "D" on the station combined characteristics.

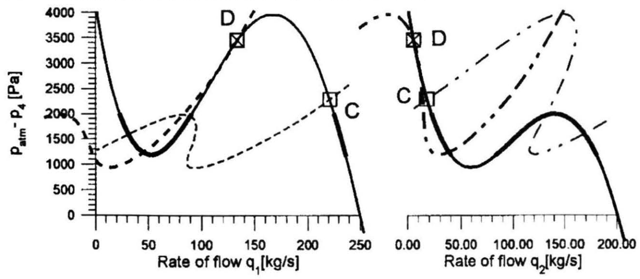

Figure 14. Locations of the operating points of the first and second fan systems, for the example given in Figure 14.

Time series of flow rate during a transition towards the operating point "D" on the rising portion of the equivalent characteristics are shown in Figure 15.

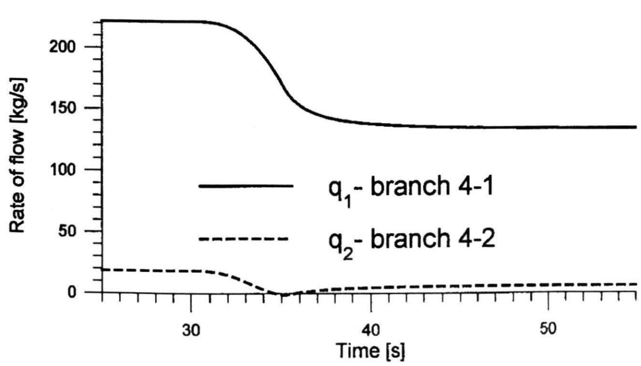

Figure 15. Flow transient while moving from the point "C" to reach the point "D" in Figure 14 and 15.

FINAL REMARKS

Similar calculations can be done for three fans [Krawczyk, 1997]. The conclusions are that operating point of the fan station wherein two or more fan systems operate on the rising portions of their characteristic curves will be unstable. Besides, should one of the fans have its operating points on the rising part then the operating points of other fans must be located on sufficiently steep falling portions of the characteristic curves to satisfy condition analogous to (13).

In the paper the results of stability analyses are presented together with the computer simulation of one-dimensional, non-compressible flow models. Additionally, it was assumed that the pressure-volume curves plotted for the steady states will be also relevant for transient states. For almost- steady states the incompressible flow model applied to study the branch flows in the neighborhood of the fan stations provides a good approximation. Therefore, it can be assumed that the lack of stability predicted using that criterion will be also encountered in real flows. The calculations made for one-dimensional compressible models confirm that the equilibrium points failing to meet the conditions (12) and (13) will not be stable. To fully verify this assumption it would be necessary to run several experiments using the physical models or real flows.

The incompressible flow model does not allow to predict other forms of stability losses, such as those due to pressure waves and generation of self-excited vibrations, which were studied experimentally and the mathematical models were provided [Kazakiewicz 1957; Dzidziguri and Durmishidze 1966; Trutwin 1997 and Bystroń 1998]. That is why the conditions (12) and (13) may prove very helpful, but only in preliminary selection of the possible operating points; as they do not guarantee that the remaining operating points must necessarily be stable.

Special attention should be given to the case when at least one fan has its operating point on the rising portion of its characteristics, even though the combined characteristic of the whole fan system should be falling.

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